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THE USE OF SF_6 TO DETERMINE LEAKAGES FROM AN AUXILIARY VENTILATION DUCT IN A LONG SINGLE HEADING

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THE USE OF SF_6 TO DETERMINE LEAKAGES FROM AN AUXILIARY VENTILATION DUCT IN A LONG SINGLE HEADING

by

A.W. Stokes*

ABSTRACT

SF_6 has numerous uses in resolving complex ventilation problems. The Cape Breton Coal Research Laboratory is committed to developing an instrument capable of measuring SF_6 in real-time underground. If this is achieved the uses for SF_6 underground will be greatly extended. This report documents a field experiment which was undertaken to collect the control data with which prototype real-time instruments currently being built in-house will be compared. The test used the standard technique of collecting grab samples for analysis back in the laboratory. The results have been analysed and prepared in a way that will enable easy comparison with direct real-time curves from the tunnel at a later date.

The report shows how tracer gas can be used to provide a speedy analysis of a long length of ventilation duct using a single injection. This technique has great potential for installations like the 7.6 m diameter No. 2 Tunnel of the Donkin Morien mine development where the duct is not easily accessible for more conventional measurement techniques.

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DÉTERMINATION DES FUITES DANS LE CANAL D'AÉRAGE AUXILIAIRE D'UN LONG FRONT DE TAILLE AU MOYEN DU SF_6

par

A. W. Stokes*

RÉSUMÉ

Le SF_6 se prête à de nombreux modes d'emploi visant à solutionner les problèmes complexes d'aérage. Le Laboratoire de recherche sur le charbon du Cap-Breton s'est engagé a mettre au point un appareil capable de mesurer le SF_6 en temps réel dans les exploitations souterraines. Si on réussi à mettre au point un tel appareil, l'utilisation du SF_6 dans les exploitations souterraines prendra un nouvel essor. Le rapport présente les résultats d'un essai effectué sur le terrain en vue de faire la collecte de données qui serviront à déterminer les paramètres qui seront utilisés pour comparer les appareils modèles de mesure en temps réel que le laboratoire est à mettre au point. Pour les besoins de l'essai, on a utilisé les méthodes ordinaires de cueillette d'échantillons pris au hasard, lesquels font ensuite l'objet d'une analyse en laboratoire. L'analyse et la compilation des résultats a été faite de façon à simplifier la comparaison avec les enregistrements graphiques en temps réel en provenance du tunnel, à une date ultérieure.

L'auteur décrit la manière d'employer le gaz trace en une seule injection pour effectuer l'analyse rapide d'une longueur d'un canal d'aérage. Cette méthode offre de nombreuses possibilités aux installations dont le canal d'aérage est difficilement accessible au moyen des méthodes classiques, tel le tunnel n° 2 du chantier Donkin-Morien dont le canal d'aérage a un diamètre de 7,6 m.

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INTRODUCTION

The Cape Breton Coal Research Laboratory (CBCRL) is actively investigating the use of tracer gases for solving mine ventilation and related problems. To date, several studies have been completed using sulphur hexafluoride (SF_6) and propane (C_3H_8) as tracer gases. Propane was used to investigate the ventilation system of a full face tunnel boring machine on the surface prior to the machine being used underground. A flame ionisation detector was used with a total hydrocarbon analyser to obtain a real-time detection in the cutting head exhaust airstream. This type of analysis proved very flexible and allowed a good evaluation of the TBM's ventilation system. Propane cannot be used in an underground coal mine due to the presence of other hydrocarbons, such as methane, and permissibility problems with the detection equipment. Most work with tracer gases in coal mines has therefore been limited to using either SF_6 or nitrous oxide as the tracer gas. These are collected as grab samples from underground and analysed on surface using a gas chromatograph. The grab sampling technique is adequate for most uses of SF_6, but the ability to measure in real-time underground would open up several new uses. For this reason CBCRL is presently investigating ways of achieving this aim.

There are many complications to measuring SF_6 in a real-time mode in a coal mine environment. CBCRL is therefore taking an intermediate step by developing a pseudo real-time unit - a gas chromatograph capable of analysing a sample every 10 seconds. This instrument, it is hoped, will be able to cope the rigours of the coal mine environment. An underground measurement of the SF_6 concentration in an airstream every 10 seconds would facilitate the collection of a much higher grade of data than is presently possible by taking grab samples for laboratory analysis.

Prior to using this instrument in a coal mine it is to be tested in the hard rock mines of Elliot Lake (those mines do not have the restrictions of permissibility that are demanded by collieries). For that intermediate step the instruments will require only small modifications from their prototype stage as developed on the laboratory bench.

Before testing in Elliot Lake the gas chromatograph will have a preliminary field trial in Cape Breton. The Donkin-Morien development site has two long, large diameter auxiliary ventilated tunnels. These provide a

mine like ventilation system which can be monitored from surface (allowing the use of uncertified instrumentation in fresh air). By doing investigations in these tunnels a two-fold objective will be achieved. Firstly, it will allow us to investigate the performance of tracer gas in analysing the tunnel ventilation system and flow in the tunnel itself. That is useful since some of the proposed experiments in the Elliot Lake trials will be in tunnels of similar dimensions incorporating auxiliary ventilation systems. Secondly, the easy access to the tunnels makes them ideal for experimental control. The on-site performance of the gas chromatograph can be compared with the more conventional sampling methods. This report describes the investigation undertaken to achieve the first objective and to establish the control data (grab sampling) to allow the second objective to be achieved at a later date.

NO. 2 TUNNEL VENTILATION SYSTEM

The Donkin-Morien development consists of two tunnels driven to intersect a coal block 3.58 km off the coast. One of the tunnels, the No. 2 Tunnel, was completed in late 1984. This was driven by a 7.6 m diameter full face tunnel boring machine. Ventilation of this tunnel is provided by two high pressure centrifugal fans which feed air into two parallel auxiliary ventilation ducts which extend to the end of the tunnel. These are 1.07 m in diameter and made from 100 m lengths of heavy duty woven polyster/nylon fabric coated with PVC. They provide low airflow resistance and, when in good condition, excellent leakage characteristics allowing the design quantity of 15 m^3/s to be delivered from the end of each duct. At present there is no mining activity in the tunnel as the TBM has been removed, but the ventilation is being maintained to keep the tunnel purged of methane which is released from the exposed strata.

Figure 1 is a schematic showing the layout of the No. 2 Tunnel and its ventilation system. The first 1100 m of the tunnel has a -20 to -10 percent grade which changes to a 1 percent grade for the remaining 2400 m. Just inbye the concrete portal a shaft intersects the tunnel from surface. This was used to lower the TBM into place at the start of the drivage. The two forcing centrifugal fans are located in line with the tunnel between the shaft and the portal. The ducts from these run down the shaft and are hung in the uppoer portion of the tunnel from the steel support sets. The west

side duct line is unbroken and discharges all its air close to the tunnel face. The east side duct has a 'T' in it close to the face. Approximately half its air is diverted through this 'T' to ventilate a short cross-cut which has been driven in the coal, the remainder is discharged at the main tunnel face.

All of the air discharged from the ducts flows back to the surface in the main body of the tunnel exhausting via both the portal and the shaft.

OBJECTIVES OF THE TRACER GAS INJECTION

An additional purpose for this field study was to demonstrate to a visiting scientist from ELMRL the techniques which have been adopted by CBCRL in tracer gas studies. To accomplish this, the experiment was extended to incorporate as many field operational procedures as possible. The following parameters were measured or investigated:

- direct measurement of the tunnel airflow,
- direct measurement of the airflow in the west side duct and by difference the flow in the east side duct,
- an assessment of the air leakage from the west side duct,
- tracer gas distribution across the profile of the tunnel and its relation to the velocity profile,
- determination of the amount of recirculation of air back into the tunnel, and
- residence time of air from the west side duct in the tunnel.

THE TRACER GAS INJECTION

The tracer gas used for this study was SF_6. A continuous steady stream of 0.846 cc/s of pure SF_6 was released from a lecture bottle through a critical orifice into the inlet of the west side fan. The time of initial release of the gas was recorded to allow all events subsequently measured to be related to a finite time. The flow rate of the gas was measured directly using a soap bubble flow meter and cross-checked with the measured mass lost from the lecture bottle.

DUCT SAMPLING

Once the gas had had sufficient time to achieve steady state in the duct close to the fan, two air samples were drawn from it about 15 m from the

fan. One was a spot sample collected from the centre of the duct. The other was a sweep sample drawn from the entire cross-sectional area of the duct - hopefully giving a sample containing the average concentration of the SF_6 in the airstream. After 2 hours of SF_6 release it was assumed that conditions in the tunnel were at or close to, steady state by this time the exhaust air from the tunnel contained significant concentrations of SF_6. A sample of air was drawn from the east side duct as a point approximately 15 m from the fan. Any measureable concentration of SF_6 in this airstream would indicate recirculation of return air from the tunnel.

The concentrations measured in the samples from the west side duct were as follows:

Spot Sample = 51.08 ppb
Sweep Sample = 42.87 ppb

These values were used with the equation,

$$Q = \frac{\dot{v}}{c} \qquad \text{Eq 1}$$

where, Q is the airflow (m^3/s)

$\dot{v}$ is the volume flow of the tracer into the airstream (m^3/s)

and c is the measured concentration of tracer in the airstream

to calculate the following duct flows:

Spot Sample = 16.56 m^3/s
Sweep Sample = 19.73 m^3/s

These values compare well with independent pitot tube determinations made of the quantity by CBDC's ventilation personnel (1). They measured 19.48 m^3/s at the same point in the west side duct. These results suggest that there was some concentration profile of SF_6 across the duct with higher than average concentrations towards the centre. The collecting of an integrated sample from the entire cross-section appears to provide a more representative average concentration.

The air sample collected from the east side duct contained no measureable concentration of SF_6. This shows that on the day of the survey

recirculation via the east side duct was not taking place. However on the day in question the general wind direction was from NE to SW (see Figure 1). This would not be condusive to recirculation. It is probable that a repetition of this test on a day when the wind direction was different would show some recirculation.

PROFILE SAMPLING IN THE TUNNEL

The finished cross-sectional area of the TBM driven tunnel is 40.2 m^2. In this are the two ventilation ducts and a conveyor structure, the relative positions of which are shown in Figure 2. The tunnel walls are smooth as mining tunnels go and the air velocity is about 1 m/s. Spot samples were collected from ten locations across the tunnel cross-section as shown in Figure 2. These samples were collected some two and a half hours after the start of the release. Rough calculations suggested that the elapsed time should have allowed steady state conditions to be achieved. The air velocities at each of the ten sampling points were measured with a vane anemometer.

As will be shown in the next section, this profile sampling was not done in steady state conditions, but just prior to these being established. The concentrations measured in the tunnel were therefore taken as the main front of the SF_6 coming out from the end of the duct was moving past the sampling location in the tunnel.

The diagram in Figure 3 is another schematic of the tunnel cross-section on which is marked the measured SF_6 concentrations and air velocities next to the appropriate spatial location at which they were measured. It is not possible to make any definitive conclusions from these results, but some general observations can be made. The SF_6 concentrations are higher for the points near to the centre to the tunnel, especially along the vertical centre line of the profile. The air velocities were not measured accurately as the only anemometer available at the time was equipped for high velocity measurements. The values shown therefore serve only as an approximate relative comparison. These agree with the commonly held view that air velocities close to the tunnel walls and obstructions are generally lower than velocities measured near the centre of the cross-section in clear unobstructed areas.

The average SF_6 concentration of all ten spot samples was 22.88 ppb. This agrees closely with a sweep sample which was collected from

the same cross-section immediately after the last spot sample. This contained a 23.75 ppb concentration of SF_6. The slightly higher value may be due to an increase in SF_6 concentrations occurring during the profile sampling (i.e. tunnel was not at SF_6 steady state).

SHAFT SAMPLING

The most interesting aspect of this survey were the results of samples which were collected from the return air in the general body of the tunnel close to the base of the shaft (see Figure 1). Air was drawn from this part of the tunnel through a 50 m length of tygon tubing by an MSA fixed flow pump. Samples from the pump were collected in Tedlar sampling bags at regular intervals ranging from every 2 minutes just after the release of the SF_6 to every 10 minutes towards the end of the survey.

Figure 4 shows a graph of the SF_6 concentrations measured in the bag samples versus the elapsed time since the start of the release. The eventual steady state concentration measured at 1500 hrs was close to 24 ppb. Using this value in equation 1 the tunnel airflow was 35.25 m^3/s. By difference this makes the airflow in the east side duct 15.52 m^3/s (35.25 - 19.79). These values also agree closely with the independent measurements made by CBDC:

$$\text{East Side Duct} = 21.82\ m^3/s$$

The dashed line drawn on the graph in Figure 4 shows the theoretical concentration time curve for a leakless duct and plug flow in the tunnel. Although plug flow would never occur in practice a leakless duct would produce a curve with the same t_{50} time as the theoretical curve shown.

$$\text{Cross-sectional area of a ventilation duct} = 1.79\ m^2$$

$$\text{Travel time for duct} = \frac{3500\ m \times 1.79\ m^2}{19.79\ m^3/s} = 3.6\ \text{secs}$$

$$\text{Free cross-section of tunnel avalable for airflow} = 38.41\ m^2$$

$$\therefore \text{Travel time for tunnel} = \frac{3500\ m \times 38.41\ m^2}{35.25\ m^3/s} = 3814\ \text{secs}$$

$$\text{Total } (t_{50}) \text{ travel time} = 4130\ \text{secs} = 68.8\ \text{mins}$$

A substantial concentration of SF_6 was measured in the first sample collected at the shaft only 2 minutes after the opening of the valve on the lecture bottle. Obviously this must have come from a leaky section of duct close to the shaft. After the quick initial rise in the concentration the increase became more gradual and regular. This is indicative of a series of small leaks in the duct distributed along its length. Between 60 and 80 minutes of lapsed time the gradient of the concentration profile again increases slightly returning close to the previous slope between the 80 to 115 minutes period. The slight increase between 60 to 80 minutes is probably attributable to a large single leak in a short section of duct. The increase in the SF_6 concentration in the return airstream would then be diffused laterally in the airstream as it moved up the tunnel. From 115 minutes to 140 minutes there is a sharp increase in the concentration gradient. This is undoubtedly SF_6 contained in the air which was discharged from the duct at the end of the tunnel.

Using the percentage scale on the right hand side absissa, the volume of air which reached the end of the tunnel can be determined. The point on the curve coincident with the sharp change in gradient (115 minutes) represents the start of the SF_6 profile from the end of the duct. This equates to 56 percent on the percentage removal axis. Therefore the percentage of the fan quantity reaching the end of the duct was 44 percent (100 - 56%), or 8.7 m^3/s of air (19.79 x 0.44). The same measurement made by CBDC with a pitot tube was 8.1 m^3/s.

Figure 5 is a differentiation of the curve in Figure 4. This has previously been shown to be the concentration/time curve which would have been obtained by pulse injecting a volume of tracer gas into the inlet of the fan at time zero (2). The individual peaks more clearly highlight the major leakages from the duct. The magnitude of each individual leak can be determined by the relative area under each peak (or more directly from Figure 4). The approximate location of these leaks within the tunnel can also be determined using Figures 4 and 5. Longitudinal dispersion in the tunnel will tend to blur the spikes from individual leakage points in the duct. The concentration/time curve measured at the outlet of the tunnel includes any such longitudinal dispersion.

The travel time of the tracer gas which forms a peak from the hole in the duct to the surface is dependent on the average air velocity in the

tunnel and duct between these two points. This information can be found from Figures 4 and 5. The values for the average velocities can then in turn be used to determine the distance of the leak point from the surface. The presence of a second leaky duct in parallel with the one under investigation presents a complication since the leakage from it is unkown. However, from measurements made by CBDC it would seem that the magnitude of the leakage from the east side duct is similar to the west side duct. So to illustrate the technique assume that the east side leakage is of the same magnitude and distributed in the same pattern along the duct as the west side. Looking at the curves in Figures 4 and 5 it should be possible to calculate the length of duct in the tunnel by analysing the last major peak.

The peak from this gas arrived back at the shaft 127 minutes after the tracer release (from Figure 5). An integration of the curve in Figure 4 between time zero and 126 minutes gives an average concentration of tracer gas of 11 ppb. This represents an average leakage from the duct over this time/length of 44 percent or 8.71 m^3/s. The average air velocity in the duct, V_d, is therefore:

$$\frac{19.79 \times (1 - 0.44)}{0.8938} = 11.94 \text{ m/sec}$$

and the average velocity in the tunnel, V_t, is:

$$\frac{35.25 \times (1 - 0.44)}{38.41} = 0.51 \text{ m/sec}$$

The following equation gives the distance into the tunnel that the leak occurred:

$$d_\rho = \frac{t \cdot V_d \cdot V_t}{(V_d + V_t)} \qquad \text{Eq 2}$$

where, d_ρ = the distance into the tunnel

t = is the elapsed time before the peak report back to the tunnel inlet

Substituting in the calculated velocities into equation 2, we get:

$$d_t = \frac{127 \times 60 \times 11.94 \times 0.51}{(11.94 + 0.51)} = 3754 \text{ m}$$

This compares very well with the actual tunnel length of 3580 m. The difference between the calculated and actual values can probably be attributed to the different leakage from the west side duct which made the average tunnel velocity slightly less than calculated.

CONCLUSIONS

The No. 2 Tunnel at Donkin-Morien mine provides an easily accessible mine ventilation system which can be analysed from the surface. The tracer gas sulphur hexafluoride was used successfully to determine several parameters of the auxiliary ventilation system including both duct flows, the tunnel airflow, the leakage from the west side duct and the distribution of the leakage along the duct. This system of auxiliary ventilation analysis provides an easy method for investigating long auxiliary ventilated heading where access to the ducting in the tunnel is not easy or possible e.g. large diameter TBM driven tunnels. A single injection of tracer gas will define all the listed parameters.

The results of this survey will provide a good data set with which to compare the performance of the prototype gas chromatographs presently under construction at CBCRL. These will be field tested at Donkin-Morien No. 2 Tunnel prior to their use in Elliot Lake.

For auxiliary ventilated heading with two ducts the analysis would be improved by the use of two different tracer gases simultaneously; i.e. one injected into each duct. If possible this will be attempted in the near future.

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2. Stokes, A.W. and Stewart, D.B.; "Cutting head ventilation of a full face tunnel boring machine."; For presentation at and publication in the tunproceedings of the 21st International Conference of Safety in Mines Research Institutes; Sydney, Australia; October 1985.

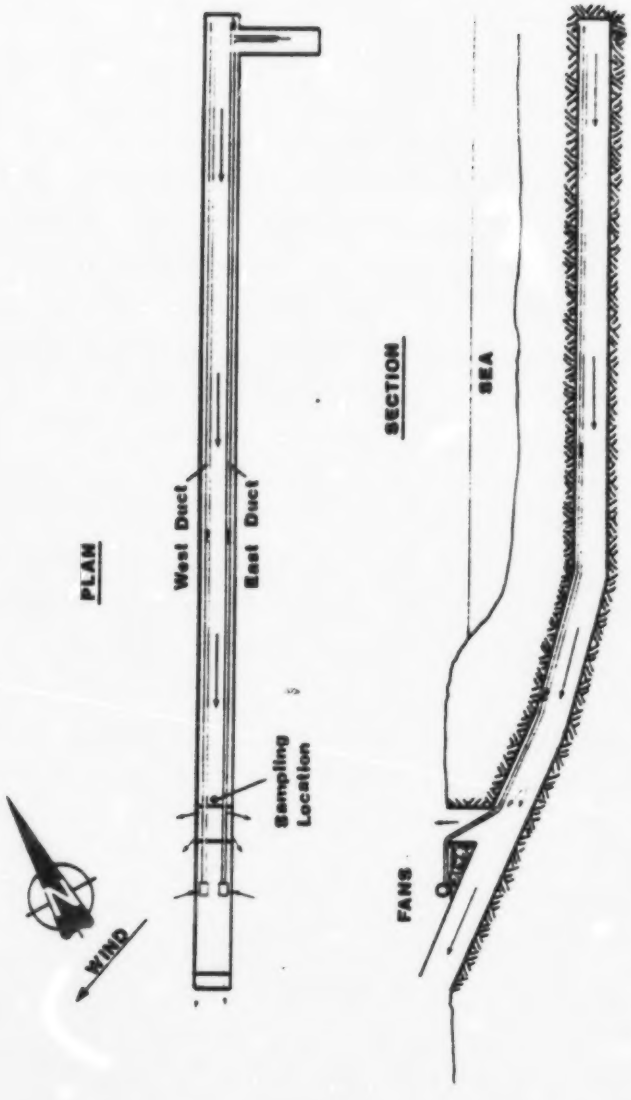

Figure 1 - The Donkin-Morien No. 2 Tunnel and its ventilation system

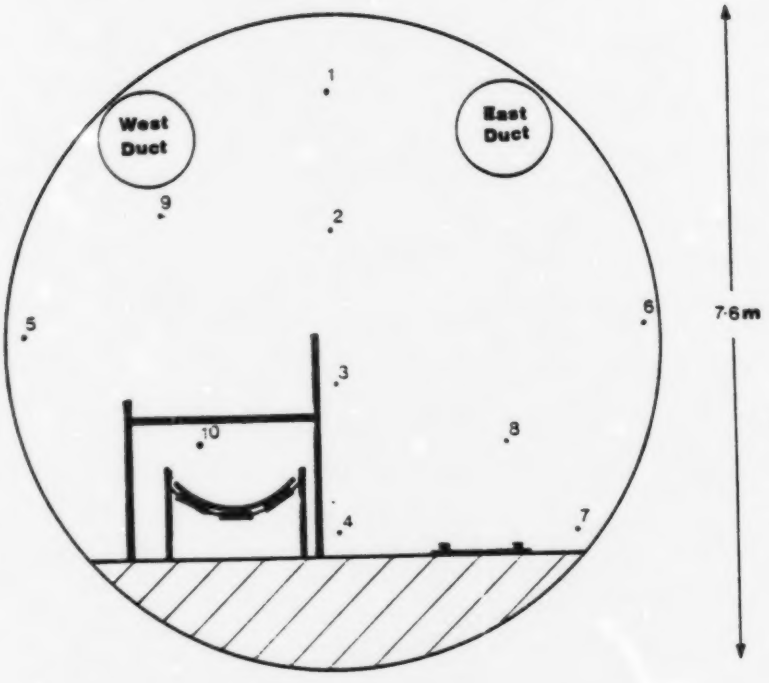

Figure 2 - Spatial coordinates of sampling points in tunnel (looking into the tunnel)

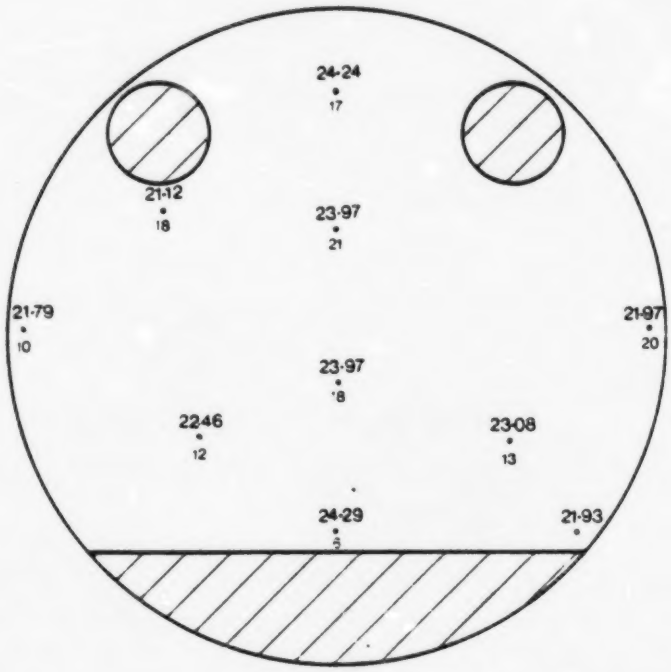

Figure 3 - SF_6 concentrations measured across tunnel and approximate relative velocities

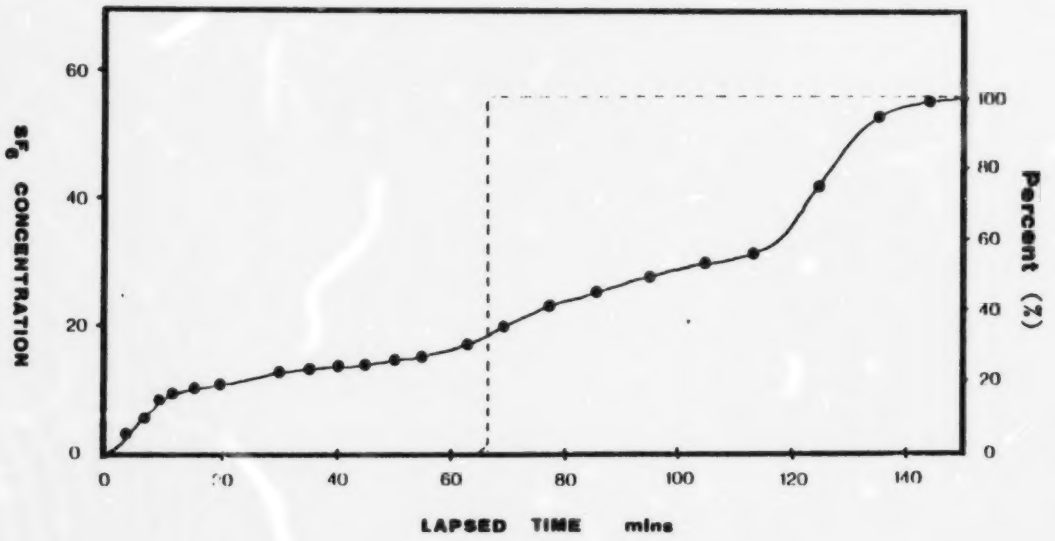

Figure 4 - SF_6 concentrations measured in the exhaust air from the tunnel versus the lapsed time since the start of the injection

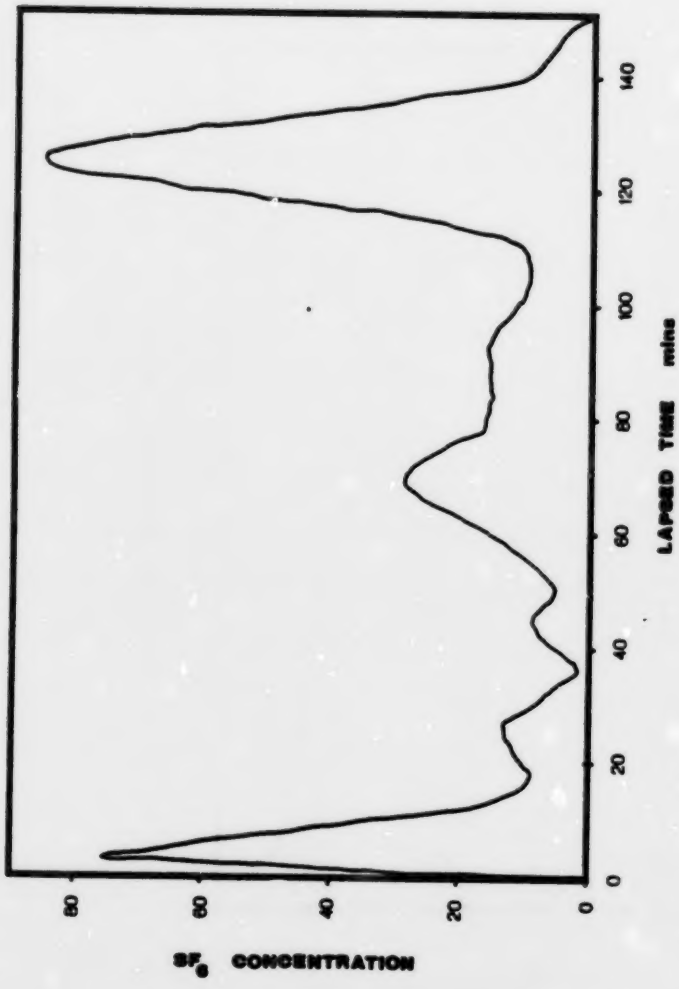

Figure 5 - Differentiation of the curve shown in Figure 4